IMPACT OF SUPERCONDUCTING CAVITIES ON LEP2 DESIGN

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Abstract
The Large Electron Positron (LEP) collider at CERN is being upgraded in energy to about 90 GeV per beam (above the W-pair-production threshold). This requires very large RF voltage (more than 2000 MV) to reach the design energy. In addition, the machine transverse broadband impedance must be kept as small as possible to maximize single-bunch currents and hence luminosity. Superconducting cavities are best suited, if not the only choice, for fulfilling these requirements. After a description of the LEP2 cavities and couplers and their technical difficulties, the problem of stability of the RF system with beam is addressed.

1. THE LEP MACHINE — ENERGY AND LUMINOSITY

LEP, the largest particle accelerator in the world, is an electron-positron collider located close to Geneva (Switzerland). Its circumference, almost 27 km long, straddles the Swiss-French border between Lake Geneva and the Jura mountains. To minimize the risks associated with the difficult geological areas in the Jura limestone, the plane of the machine is not horizontal, but slightly tilted with a maximum slope of 1.42%. Table 1 shows the major LEP parameters, especially those relevant to the acceleration system.

Table 1

A few LEP1 parameters

Circumference		26 658 m
Revolution frequency		11.245 kHz
Injection energy		20 GeV
Operating energy		45 GeV
Number of bunches per beam		4
Intensity per bunch		~ 0.75 mA
RF frequency		352.209 MHz
Harmonic number		31320
Available RF voltage (128 cavities)		340 MV
RF cavity	Length:	2.12 m
	Impedance:	28.5 MΩ (43.8 MΩ with storage cavity)

The present RF system is composed of 128 copper cavities located in the two straight sections at Point 2 and Point 6 [1]. Each cavity is a five-cell structure (total length 2.5λ). The internal diameter of the drift tubes is 100 mm. The cavity design takes advantage of the very long distance between bunches, by storing the RF energy between bunch passages in a low-loss storage cavity coupled to the accelerating structure. In fact the RF energy oscillates between storage and accelerating cavity at 8 f_{rev} (f_{rev} being the machine revolution frequency). The storage cavity is a low-loss spherical resonator, which increases the effective shunt impedance of the coupled system by more than 50% as compared to the accelerating cavity alone, and hence reduces the RF power by the same factor. Sixteen cavities are powered via a tree of magic tees, from two high-power klystrons, each driven at one of the resonant frequencies of the coupled system.

LEP was conceived from the very beginning as a machine with an energy capability much higher than the Z_0 energy (45 GeV) which is its presently operating condition. Going higher requires much more RF voltage, because of the very steep increase in synchrotron radiation. The energy lost per turn by an electron or a positron U_0 is given by:

$$U_0 = \frac{4\pi}{3}\frac{r_e}{E_0^3}\frac{E^4}{\rho} \tag{1}$$

where r_e is the classical electron radius, E_0 its rest energy and E its actual energy. ρ is the radius of curvature. At the injection energy of 20 GeV, U_0 = 4.5 MeV and at the present energy of 45 GeV, U_0 = 117 MeV, whereas U_0 = 1875 MeV is needed to reach 90 GeV, above the W pair production threshold. Note that these figures, valid for a bare machine can be somewhat changed if additional wiggler magnets are inserted in the machine. This energy upgrade from 45 to 90 GeV is called the LEP2 programme.

When synchrotron radiation is important, as in the LEP case, the energy and phase oscillations of individual particles, present as in any other machine, are damped. This is because an electron which has for instance a little excess energy compared to equilibrium, will lose more energy [in Eq. (1) the term E^4 largely dominates the $1/\rho$ term] and ultimately reach equilibrium. The damping time τ_e of this exponential decay of energy oscillations is simply given by:

$$\tau_e = \frac{E}{U_0 f_{\text{rev}}} \tag{2}$$

This effect is not very important at injection (τ_e = 395 ms) but very strong at 90 GeV (τ_e = 4.2 ms).

If there were no other effects, all electrons and positrons would end up having exactly the same energy (the equilibrium energy). This would assume that the radiated energy was lost in a continuous, smooth way. This is not the case because of the quantum nature of radiation emission; photons are emitted randomly and their energy has a broad spectrum. From the point of view of electron dynamics, this is equivalent to a noisy RF, which is known to produce a gradual increase of the synchrotron oscillation amplitude. The result of the two competing effects, radiation damping and quantum emission, is to produce an equilibrium distribution of the particle’s energy which has a gaussian shape with a typical relative width σ_e/E proportional to energy:

$$\frac{\sigma_e}{E} = \frac{E}{E_0}\sqrt{\frac{c_q}{2\rho}} \tag{3}$$

c_q being a constant of the machine.

The equilibrium energy distribution which extends theoretically to infinity is in fact limited by the RF bucket size. That part of the gaussian distribution beyond the RF separatrix on the energy axis is continuously lost. The beam lifetime is therefore limited; the beam intensity decays exponentially with a time constant τ_q (quantum lifetime) given by:

$$\tau_q = \tau_e\left(\frac{\sigma_e}{E}\right)^2 \exp\left(\frac{\Delta E^2}{2\sigma_e^2}\right) \tag{4}$$

where ΔE is the bucket height, depending on the RF voltage V_{RF}, the stable phase angle ϕ_s $\left(\sin\phi_s = U_0/V_{RF}\right)$ and the energy.

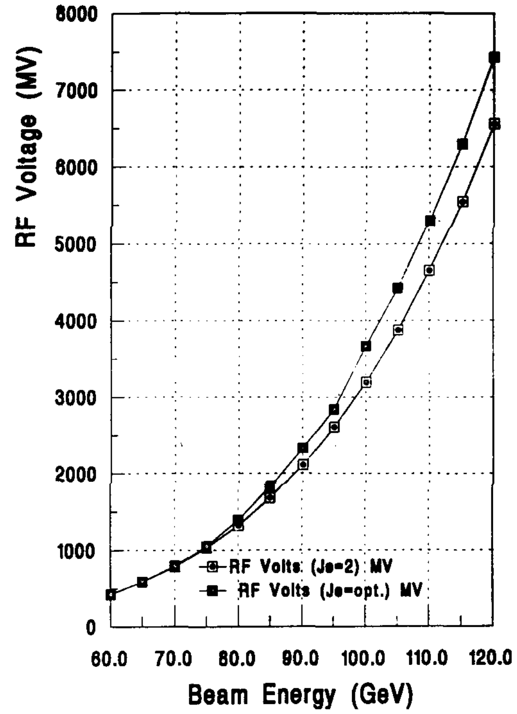

Fig. 1 RF voltage needed for a given beam energy and τ_q = 15h (two different lattices).

All ingredients are now available to evaluate the RF voltage necessary to obtain a given energy at a given quantum lifetime. Figure 1 shows the result for LEP2 energies and τ_q = 15 h, with two different lattices. The necessary RF voltage is close to 2000 MV which, if only copper cavities were used, would require about 600 cavities, that is 1.3 km of accelerating structure and, even more striking, 50 MW of RF power wasted in the cavity walls.

Other constraints are usually put on the RF voltage in LEP:

- At low energy the synchrotron tune $Q_s = f_s/f_{\text{rev}}$ (f_s = synchrotron frequency) must be kept constant to avoid synchrobetatron resonances.
- During collisions, a proper balance between the RF stations (at present in points 2 and 6) is necessary to make sure that the average collision energy is the same in all experiments (at points 2, 4, 6 and 8) and to avoid loss of machine dynamic aperture.

Besides the collision energy, the other key parameter of a collider is its luminosity L given by the equation:

$$L = \frac{N_{e^+} N_{e^-} k_b f_{\text{rev}}}{4\pi\sigma_x\sigma_y} \tag{5}$$

where N_{e^+}, N_{e^-} are the number of particles per bunch, k_b the number of bunches and σ_x, σ_y their r.m.s. transverse sizes.

In the case of to-day's LEP, the two parameters N and σ are not independent. When two high-intensity bunches collide, (the highly non-linear) space charge transverse forces that one bunch exerts on the other bunch particles, leads to an increase of the transverse beam dimensions (σ_x, σ_y). The effect is characterized by the so-called beam-beam parameter ξ_y (vertical plane, most critical):

$$\xi_y = \frac{N r_e \beta_y^*}{2\pi(E/E_0)\sigma_x\sigma_y} = \frac{N r_e}{2\pi(E/E_0)\varepsilon} \tag{6}$$

Here β_y^* is the vertical beta function of the machine at the collision point and ε the beam transverse emittance. In LEP, it can be shown that ε is proportional to $(E/E_0)^3$, which means that ξ_y decreases strongly with energy.

At 45 GeV, the present LEP operating energy, L is still limited by the beam-beam effect, but this is very unlikely to be the case at 90 GeV, for LEP2. In the situation where beam-beam is not a limitation, Eq. (5) can be written:

$$L = \frac{I_b^{\,2}}{4\pi k_b f_{\mathrm{rev}} \sigma_x \sigma_y} \tag{7}$$

$I_b = k_b N f_{\mathrm{rev}}$: beam current. There the luminosity will be limited by the total beam current and therefore the total power P_{RF} to be delivered to the two beams:

$$P_{RF} = 2\ I_b\ U_0 \tag{8}$$

Equation (7) shows that the beam current should be obtained with as few bunches as possible (k_b small), or in other words the current per bunch should be as high as possible. The limit is now at injection (20 GeV) where the so-called transverse mode coupling instability limits the current ($I_b < I_{th}$) that can be accumulated in a single bunch.

The threshold current:

$$I_{th} = \frac{2\pi\ f_{\mathrm{rev}}}{e} \frac{Q_s E}{\sum \beta_i k_i(\sigma_s)} \tag{9}$$

is inversely proportional to the total transverse machine impedance ($\sum \beta_i k_i$, where k_{i} is the transverse loss factor of the individual impedance, located at a position where the beta function is β_i). The threshold is proportional also to the synchrotron tune (running at high Q_s imposes a careful control of the synchrobetatron resonances) and to the injection energy. Thanks to new superconducting (sc) cavities installed in the LEP injector (see Section 4), the injection energy will be raised from 20 to 22 GeV, giving a straightforward 10% increase in intensity and hence luminosity.

In LEP, the transverse loss factor is dominated by the copper cavities. This is because k_{i} is, roughly speaking, inversely proportional to the cube of the vacuum tube diameter (100 mm in the case of the LEP RF cavities). With low-frequency superconducting cavities (352 MHz, iris diameter 250 mm), the transverse loss factor is reduced by a factor 8.5.

In conclusion LEP2 could not work at a useful luminosity without 352 MHz sc cavities having a low transverse impedance. This also justifies the choice of 352 MHz, which was also obviously favoured for reasons of hardware compatibility with the copper RF system.

To reduce the LEP transverse impedance further, it is foreseen that part of the copper RF system will be removed and replaced by sc cavities.

2. THE LEP2 CAVITIES

The LEP2 programme is based on a large number (~ 200) of four-cell, 352 MHz, sc cavities (Fig. 2) [2, 3]. From the beginning of the project the technique of niobium-copper was selected, partly because of the substantial savings made on niobium costs for such a large project, partly because of the high Q_0 values which can be obtained at the nominal operating accelerating field of 6 MV/m at 4.5 K and the absence of hard quenches.

The Nb-Cu technology is however delicate. Sputtering of Nb on the interior of the four-cell copper cavity is made by a magnetron-type discharge between the cylindrical Nb cathode and the cavity walls. The longitudinal position of the discharge along the cavity is controlled by an array of magnetizing coils inside the Nb cathode. The quality of the sputtered Nb layer is checked in a vertical cryostat test on the bare cavity, before any further assembly. The cavities are produced by three different European manufacturers, but all acceptance tests are carried out at CERN.

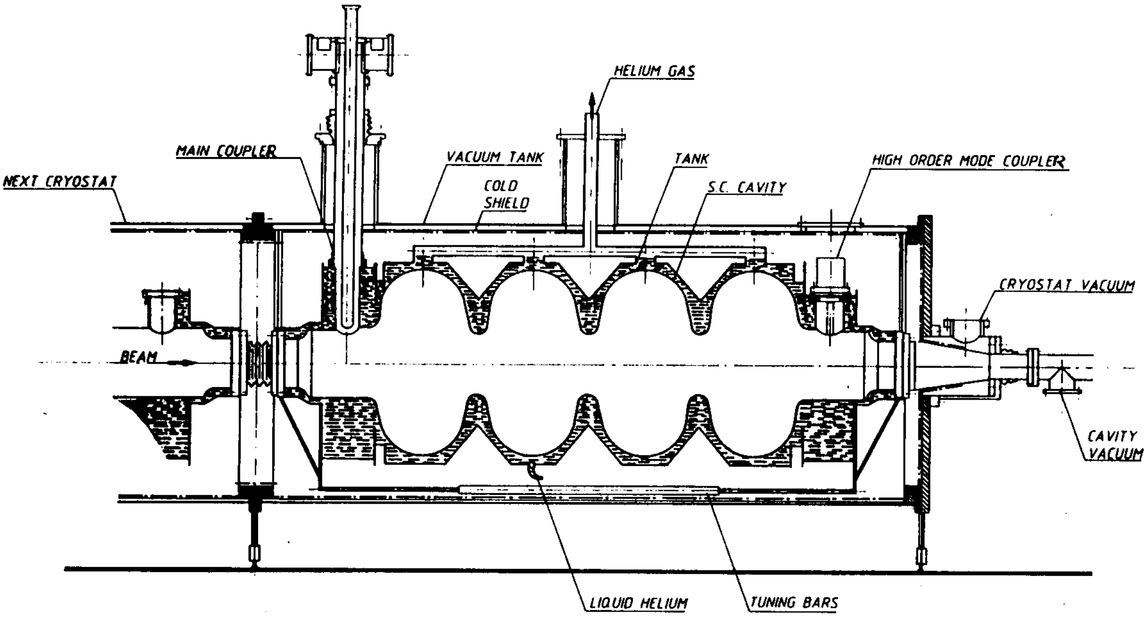

Fig. 2 LEP2 superconducting cavity

Despite the large number of cavities already produced, the success rate of the sputtering process is only about 70% at present. Critical parameters seem to be the chemical preparation of the surface, its exposure to ambient air before sputtering and the temperature of the cavity during coating. Rejected cavities are either rinsed or, in the worst cases, coated again, after stripping off the imperfect Nb layer. It is observed that the second coating is usually better than the first. The typical performance of cavities produced by industry is displayed in Fig. 3, showing a good reproducibility of the *Q(E)* curve among the three independent manufacturers. The slope of the *Q(E)* curve is characteristic of Nb/Cu technology; it is believed to be due either to the small grain size in the Nb layer or to substrate impurities migrating into it.

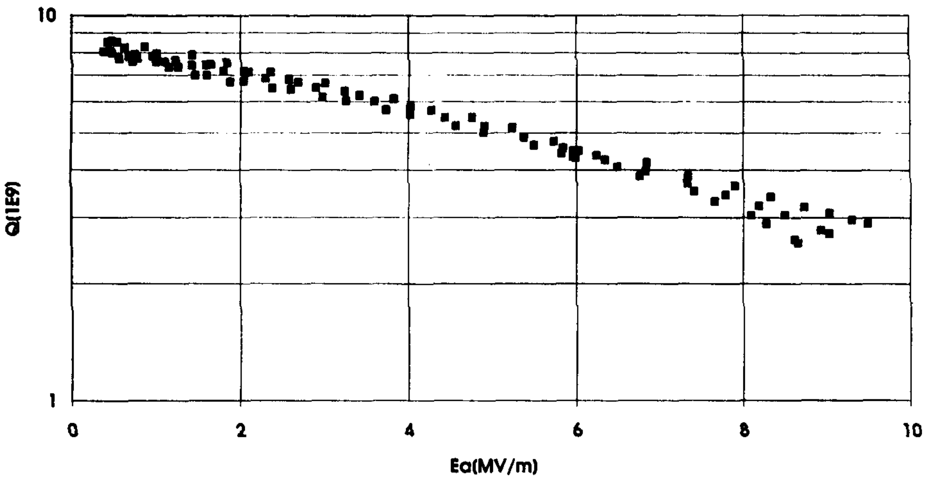

Fig. 3 *Q*(*E*) curves for cavities produced by three manufacturers

Accepted cavities are returned (under vacuum) to the firms for subsequent assembly of the helium tank, tuner bars and cryostat frame. Four such assembled cavities are then connected together in a single module. This is the second delicate operation in the overall fabrication cycle as the cavities have to be opened to air to be connected together and form a single vacuum enclosure. This is done in a clean room (class 100) and requires very experienced personnel to avoid dust contamination of the cavity surfaces. The loss of performance of the cavities after assembly into modules is fairly small ($\leq 10\%$ of Q_0 at 6 MV/m), and most of the industry-produced modules are accepted by CERN. In the case where a degradation cannot be recovered by helium processing or pulse processing [4], the cavity is taken out of the module, water-rinsed and rechecked.

LEP2 cavities are tuned with three longitudinal nickel bars connected to the two cavity end flanges. The temperature of the bars (and their length) is determined by the equilibrium between the cold return helium gas and an electric heater, which provides a slow control of the cavity tune. Fast control is obtained by the magnetostrictive effect of the nickel bars under an applied magnetic field (response time ~ 20 to 50 ms).

Mechanical cavity resonances can be harmful to LEP2 operation. When beam is present, the servo tuner keeps cavity voltage and forward power in phase (see Section 3), thus detuning the cavity. In this situation any tune modulation of the cavity (typically at the frequency of a longitudinal mechanical resonance) leads to an unwanted modulation of the RF voltage, thus limiting the overall performance. Excitation of mechanical cavity resonances (typically around 100 Hz) can be external, usually via the cryogenic system, or intrinsic to the cavity [5]. In the latter case an electroacoustic instability develops due to the dependence of the cavity tune on the RF field (Lorentz force detuning or thermal effects in the helium bath). Large modulations of the RF voltage (> 50%) and cavity phase can be observed. In theory, the fast cavity tuner could suppress this instability, if only one mechanical resonance were present. This is, unfortunately, not the case and the only practical remedy is to run the cavity closer to tune, at the expense of more RF power.

3. LEP2 COUPLERS

The main couplers of LEP2 cavities are of the coaxial line type (Fig. 4). The waveguide-to-coaxial transition is derived directly from the copper cavity coupler design, with a matching element (doorknob) in the waveguide and a warm ceramic vacuum window. The cold-warm transition is via the outer conductor of the coaxial line (thin stainless steel tube, copper coated).

The inner conductor is at room temperature (air-cooled) and forms a 75 Ω line which, compared to the original 50 Ω design, shifts upwards in power the multipacting levels in the coaxial line. The original coupler was variable with a sliding contact on the inner conductor, protected by a folded $\lambda/2$ line (choke) located inside the window area. Despite its interesting ability to adjust the cavity coupling (Q_{ext}) precisely to the waveguide distribution system, the variable coupler has been replaced by a fixed version ($Q_{ext} \cong 2 \cdot 10^6$) to avoid additional multipacting effects in the choke area.

These couplers have been plagued by multipacting effects, especially in the cold outer conductor of the coaxial line. The solution was to bias the inner conductor with a d.c. voltage of 2.5 kV which prevents any electron multiplication effect. The doorknob has been redesigned with a cylindrical kapton insulating foil which exhibits negligible RF losses. During cavity operation in LEP, the bias voltage completely suppresses the vacuum outbursts in the coupler. Another method of suppressing some multipacting levels has been successfully tested on the LEP2 couplers. It consists of injecting a second frequency in the coupler (a few MHz away from the operating RF frequency) with an amplitude of some 10 to 20% of the main RF drive. The resonance conditions necessary for multipacting to develop are strongly perturbed by the presence of this non-synchronous RF field in the coupler. Note that the cavity voltage is not affected, because of its very narrow bandwidth.

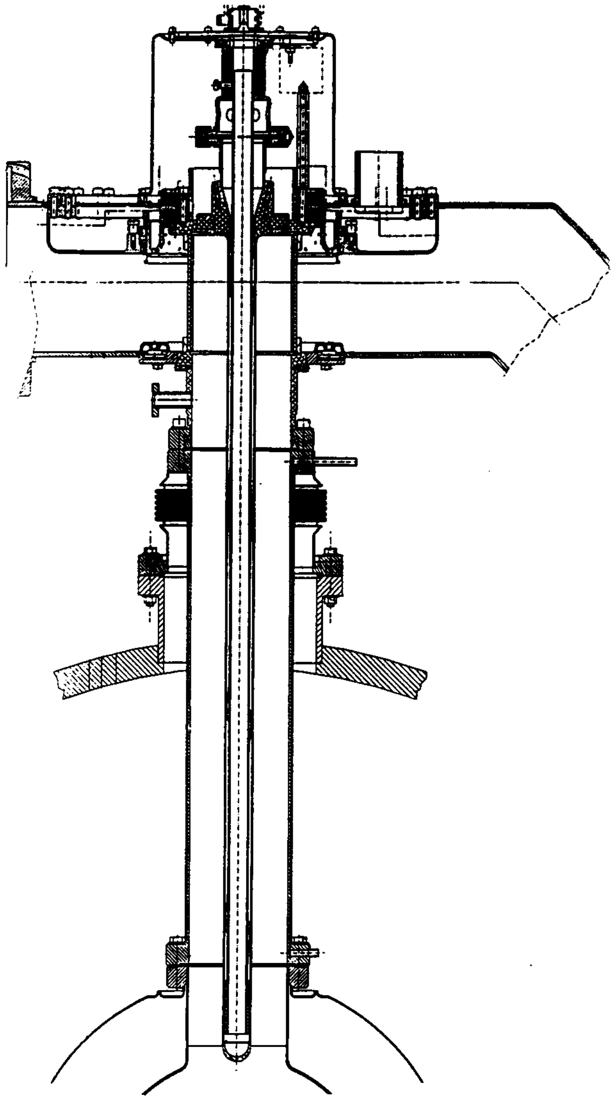

Fig. 4 The LEP2 cavity power coupler

Before installation on the cavities the couplers are processed at room temperature in travelling-wave conditions. Two identical couplers are connected on a strongly overcoupled cavity and RF power up to 200kW cw is transmitted through the couplers. It was found that processed couplers, after being mounted on the cavity (in clean-room conditions) were very difficult to condition again when the cavity was cold. This effect has been confirmed in a dedicated experiment where the outer conductor of a coupler, exposed to air, was cooled at liquid nitrogen temperature: conditioning was much more difficult with a cold than with a warm surface. As a practical conclusion, exposure to air during installation on the cavity should be kept to a strict minimum. It has also been found that baking *in situ* the RF window on the cavity, prior to cooling down, strongly reduces the conditioning time of the coupler. Proper cooling of the vacuum window during operation is important for reducing outgassing in the coupler. The Kovar rings brazed on the ceramic are copper-plated to minimize RF losses; they are brazed under axial constraint to keep a good RF contact during operation. Air cooling of the window is provided through holes in the doorknob.

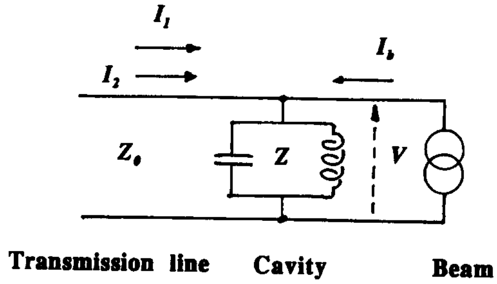

Fig. 5 Equivalent circuit of the sc cavity with beam

The critical parameter of the RF coupler is the peak electric field, which determines the multipacting levels encountered during operation. Figure 5 shows the equivalent circuit of the sc cavity (L and C elements) together with the coupler line (impedance $Z_0 = Q_{ext} \cdot R/Q$ transformed at the cavity “gap”). The beam is represented by a pure current source $\vec{I}_b$. $\vec{I}_1$ and $\vec{I}_2$ being the forward and reflected current waves on the line (measured at the cavity location or $n \cdot \lambda/2$ away), the following equations describe the circuit:

$$\vec{V} = Z\left(\vec{I}_1 + \vec{I}_b - \vec{I}_2\right) \tag{10}$$

$$\vec{V} = Z_0\left(\vec{I}_1 + \vec{I}_2\right) \tag{11}$$

where $\vec{V}$ is the cavity accelerating voltage and Z the impedance of the parallel LC circuit (purely reactive).

The forward $\left(\vec{I}_1\right)$ and reflected $\left(\vec{I}_2\right)$ waves are given by:

$$2\vec{I}_1 = \vec{V}\left(\frac{1}{Z_0} + \frac{1}{Z}\right) - \vec{I}_b \tag{12}$$

$$2\vec{I}_2 = V\left(\frac{1}{Z_0} - \frac{1}{Z}\right) + \vec{I}_b \tag{13}$$

The servo tuner compares the phase of forward wave I_1 and cavity voltage V, and brings the difference to zero by adjusting the value of the imaginary term Z. It follows that:

$$2I_1 = \frac{V}{Z_0} + I_b \sin\phi_s \tag{14}$$

$$2I_2 = \frac{V}{Z_0} - I_b \sin\phi_s \tag{15}$$

where ϕ_s is the stable phase angle ($\phi_s = +\pi/2$ for $\vec{V}$ and $\vec{I}_b$ in opposition).

Figure 6 shows the forward P_f and reflected P_r powers on the coupler line $P_f = \frac{1}{2} Z_0 I_1^2$ and $P_r = \frac{1}{2} Z_0 I_2^2$ respectively. There is matching for $V/Z_0 = I_b \sin\phi_s$, which corresponds to the optimum power transfer to the beam. Where the two waves, forward and reflected, are in phase the peak electric field in the line is proportional to the quantity $|I_1| + |I_2|$. Below the matching point $\left(V / Z_0 > I_b \sin\phi_b\right)$ Eqs. (14) and (15) show that the peak field is proportional to the cavity accelerating voltage V and independent of the beam current. Above, it becomes independent of V, but proportional to $I_b \sin\phi_s$. Going beyond the matching point changes little the power transfer to the beam, but unfortunately results in a rapid increase of the coupler peak field.

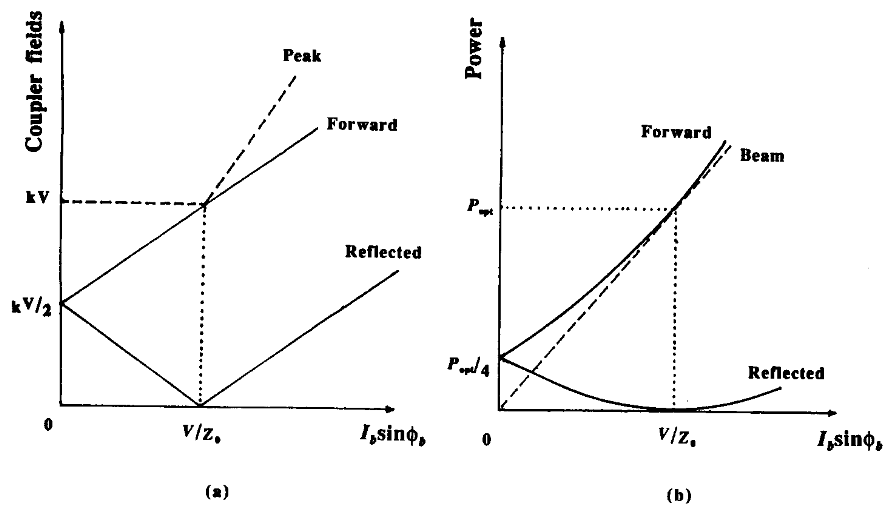

Fig. 6 Forward and reflected fields (a) and powers (b) in the coupler

The variations of Q_{ext} from cavity to cavity (due to mechanical tolerances) can be compensated by an outside $\lambda/4$ fixed transformer located in the upstream waveguide. This does not change the power transfer to the beam but leads to an increase of the coupler peak field.

It can be shown from Eq. (12) that running a cavity on tune ($1/Z = 0$), as was foreseen for suppressing electroacoustic instabilities in the cavity, will require additional power: $\Delta P = \frac{1}{2} Z_0 I_b^2 \cos^2 \phi_b$. In the case of LEP2 this additional power remains acceptable (of the order of 10 kW per coupler). However the peak field in the coupler increases by about 30%. All this shows the importance of conditioning the cavity couplers largely beyond their nominal power.

Each LEP2 cavity is equipped with two higher-order mode (HOM) couplers. They are of the “hook” type [6] where a series notch filter at the RF frequency is established with the inductance of the “hook” and its capacitance to the wall port. This type of HOM coupler is better suited to the Nb/Cu technology of LEP2 cavities. Liquid helium fills the hook tube (niobium material) to keep the notch filter elements superconducting. Adjustment of the notch frequency can be made outside the machine vacuum by elastic deformation of the base of the hook.

The power transmission capability of the HOM assembly is limited, not by the HOM coupler itself but rather by the connecting line, inside the insulation vacuum, between the cold coupler and the warm cryostat enclosure. The solution adopted is to use a rigid 25 Ω coaxial line consisting of two thin-walled stainless-steel tubes, copper-plated. Finger contacts at either end of the tubes allow some mechanical flexibility during the cryostat cooldown. It has been demonstrated experimentally that more than 850 W can be transmitted through the HOM coupler and its line, at 630 MHz (frequency of the dominant longitudinal HOM of the LEP2 cavity). This figure is largely beyond what is expected in LEP2 operation, for the largest beam currents considered; therefore the power capability of the HOM couplers is not a limitation on machine performance.

4. OPERATION WITH BEAM

At present (September 1995) ten niobium-copper modules are installed in LEP and six of them have been operated at nominal field (6 MV/m) and 7.5 mA beam current. Four more modules will go into the machine next month in order to be able to operate LEP at an intermediate energy of 65-70 GeV during a preparatory run in 1995.

Installation of the bulk of LEP2 cavities will take place in 1996, in two steps: 18 modules in spring to reach 81 GeV and another eight later in the year. Operation above the W pair threshold is expected by the end of 1996. A further increase of LEP2 energy up to about 97 GeV is foreseen for 1998 by adding 24 more modules [7].

Concerning operation with beam, the major differences with respect to copper cavities are linked to beam loading and microphonics. Beam-loading effects are much stronger in the case of LEP2 superconducting cavities, because of their much larger impedance at the RF frequency. The total impedance of the copper cavity system, as seen by the beam, is 2460 MΩ at 352 MHz; the same figure for the LEP2 superconducting cavities is more than one order of magnitude higher (~ 10^5 MΩ)

Without any special measures, the beam stability would be marginal. In particular at injection, the LEP2 operating point would be very close to the second Robinson instability limit (Fig. 7). It is recalled that the second Robinson limit corresponds to the case where the beam runs on the crest of the *generator-induced* voltage, i.e. when all RF power is transferred to the beam. In this situation the synchrotron frequency for the coherent dipole mode oscillation vanishes and stability of that mode is lost. To restore stability one could move the normal operating line ($\vec{I}_1$ and $\vec{V}$ in phase, solid line Fig. 7) further away from resonance. Unfortunately, to avoid electroacoustic instabilities, it is better to run closer to the tuned situation. There one would fall completely into the unstable region.

It has already been observed, with only a few modules in the machine that their operation is very dependent on beam parameters. This is not suprising, given the large beam-induced voltage. A typical example was the effect of a trip of a copper cavity unit (16 cavities), which increased the stable phase angle, and as a consequence decreased the sc cavities' voltage. The result was a further increase in ϕ_s, and in some cases a complete beam loss.

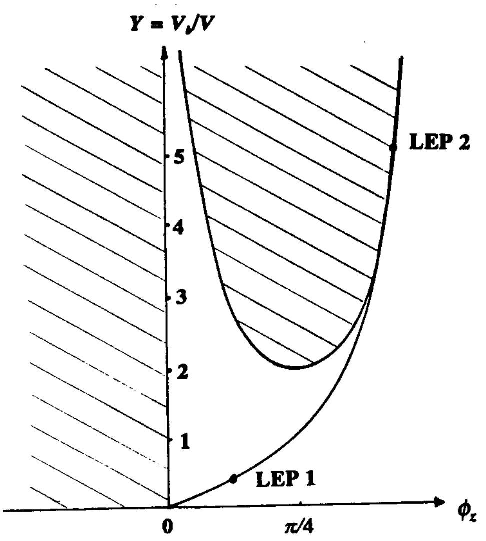

Fig. 7 Robinson stability limits:
V_b = beam-induced voltage;
ϕ_z = cavity detuning angle.

Microphonic effects are important for LEP2 cavities, because of their narrow bandwidth (±100 Hz), as compared to the LEP copper cavities (±4 kHz) and their mechanical construction (sheet-metal vessel, suspended at either end). Excitation of mechanical vibrations from the cryogenic system or other sources is very difficult to avoid completely. Large oscillations due to electroacoustic instabilities are suppressed by running the cavities closer to the tuned condition. This is achieved by changing the phase set point of the servo tuner on all eight cavities driven by the same klystron. Changing the set point of only the unstable cavity will primarily increase the voltage on that particular cavity (at constant RF drive) and is very likely to enhance the instability. In any case, adjusting the servotuner set points means changing the phase of the cavity with respect to the reference RF, which is undesirable for maximizing the overall available accelerating voltage.

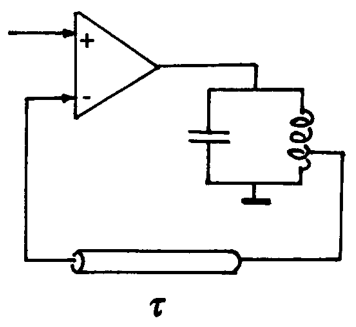

Fig. 8 Principle of RF feedback loop

In order to overcome all these difficulties, a fast RF feedback system is being implemented on all modules now installed in LEP. The total RF voltage seen by the beam when crossing the eight cavities driven by a common klystron, is reconstructed from the field-probe signals of each cavity. Great care must be applied to the calibration of the probes and cable connections (in amplitude and phase) to ensure that the overall vector sum signal is a faithful representation of the RF voltage experienced by the beam. The "vector sum" signal is maintained equal to the demanded RF voltage by the action of an RF feedback loop (Fig. 8) The loop gain, at resonance is about 30 dB, sufficient to reduce the equivalent impedance of sc cavities down to the LEP1 level, and to correct any phase variations on the cavities (either from residual microphonics, or from various phase settings of the servo-tuners).

RF feedback is a very powerful technique for dealing with beam-loading effects. The minimum achievable impedance, at the fundamental cavity frequency, is given by:

$$R_{\min} = 4\frac{R}{Q} f_{RF}\tau \qquad (16)$$

where τ is the overall delay in the feedback path. In the case of LEP2, the overall gain is rather limited by the quality of the “vector sum” reconstruction.

This is not the case for the sc cavities used in the LEP injector (the multipurpose SPS machine, which accelerates protons and leptons on alternate cycles). Here reduction of impedance is critical, especially for the very high-intensity proton beam: it is achieved by proper filtering of all four cavity modes. The loop delay (500 ns) is essentially determined by the distance in frequency between the $3\pi/4$ and π modes (about 1 MHz) which corresponds to a 180° phase rotation. In addition to the short delay RF feedback, a complementary loop with an overall delay of one machine turn (23 μs) is used to further reduce the cavity impedance. Figure 9 shows the pulsed RF waveform obtained on the SPS sc cavities, together with the demanded power from the tetrode power generator.

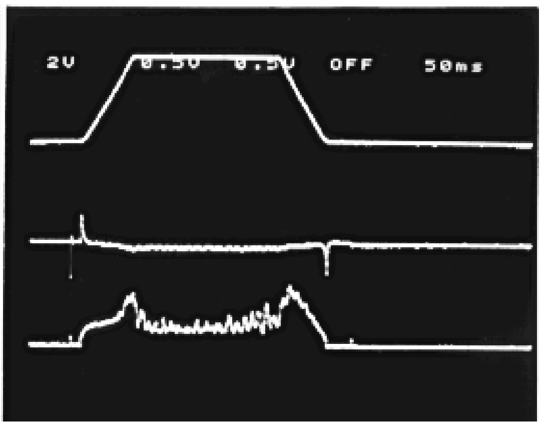

Fig. 9 Pulsed RF waveform on SPS sc cavities (50 ms/div)

Top: Cavity voltage (peak = 7.5 MV)
Middle: Tuner error signal
Bottom: Tetrode drive

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